

Discovery of optical pulsations in V2116 Ophiuchi \equiv GX 1+4¹

Francisco J. Jablonski, Marildo G. Pereira, João Braga

Divisão de Astrofísica

Instituto Nacional de Pesquisas Espaciais

12201-970 São José dos Campos, SP, Brazil

chico@das.inpe.br, marildo@das.inpe.br, braga@das.inpe.br

Clemens D. Gneiding²

CNPq/Laboratório Nacional de Astrofísica

37500 Itajubá, MG, Brazil

clemens@lna.br

ABSTRACT

We report the detection of pulsations with ~ 124 s period in V2116 Oph, the optical counterpart of the low-mass X-ray binary GX 1+4. The pulsations are sinusoidal with modulation amplitude of up to 4% in blue light and were observed in ten different observing sessions during 1996 April–August using a CCD photometer at the 1.6-m and 0.6-m telescopes of Laboratório Nacional de Astrofísica, in Brazil. The pulsations were also observed with the *UBVRI* fast photometer. With only one exception the observed optical periods are consistent with those observed by the BATSE instrument on board the *Compton Gamma Ray Observatory* at the same epoch. There is a definite correlation between the observability of pulsations and the optical brightness of the system: V2116 Oph had R magnitude in the range 15.3–15.5 when the pulsed signal was detected, and $R = 16.0 - 17.7$ when no pulsations were present. The discovery makes GX 1+4 only the third of ~ 35 accretion-powered X-ray pulsars to be firmly detected as a pulsating source in the optical. The presence of flickering and pulsations in V2116 Oph adds strong evidence for an accretion disk scenario in this system. The absolute magnitude of the pulsed component on 1996 May 27 is estimated to be $M_V \sim -1.5$. The implied dimensions for the emitting region are $1.1R_\odot$, $3.2R_\odot$, and $7.0R_\odot$, for black-body spectral distributions with $T = 10^5$ K, 2×10^4 K, and 1×10^4 K, respectively.

Subject headings: stars: individual (V2116 Oph) — pulsars: individual (GX 1+4) — stars: oscillations — stars: neutron — X-rays: stars

¹Based on data collected at CNPq/Laboratório Nacional de Astrofísica, Brazil

²Also Instituto Nacional de Pesquisas Espaciais, Brazil

1. Introduction

GX 1+4 is a low-mass X-ray binary (LMXB) well known for its unique characteristics such as extended high/low states (McClintock & Leventhal 1989; Mony et al. 1991; Makishima et al. 1988), luminosity of up to $\sim 10^{38}$ erg/s in the high state (Rao et al. 1994; Nagase 1989), the hardest spectrum of all X-ray binaries (with $kT \sim 35 - 55$ keV in a thermal bremsstrahlung model) (Laurent et al. 1989; Staubert et al. 1995; Predehl, Friedrich & Staubert 1995) and the fastest recorded rate of change of period amongst the persistent X-ray pulsars ($\dot{P}/P \sim -2\%/yr$ in the 1970s) (Nagase 1989). The optical counterpart of GX 1+4 was identified by Glass & Feast (1973) and confirmed recently by an improved X-ray position obtained with the ROSAT satellite (Predehl et al. 1995). Davidsen et al. (1977) showed that V2116 Oph has many characteristics of a symbiotic system, with the late-type star being classified as M6 III. Shahbaz et al. (1996) classify the late-type spectrum as M5 III. The absorption spectrum of V2116 Oph redward of $H\alpha$ is very similar to the spectrum of NSV 11776 (Cieslinski, Elizalde & Steiner 1994) which is classified as M4 III or later. Davidsen et al. (1977) point out a well defined excess of blue light in the spectrum, and that $H\alpha$, as well as the (blue) continuum, show variability.

Recent low-time-resolution photometric studies have shown interesting results like the approximately simultaneous $H\alpha$ and X-ray flaring activity (Manchanda et al. 1995; Greenhill et al. 1995) and the very low levels of $H\alpha$ emission (Sood et al. 1996) following the X-ray low-state in which GX 1+4 entered on 1996 August 18 (Chakrabarty & Prince 1996).

Despite all of the interesting features shown by the X-ray source, surprisingly little optical photometry work has been done with good time resolution. In the sole short-term variability study of this system performed so far (Krzeminski & Priedhorski 1978), a search for optical pulsations

in $H\alpha$ established upper limits of 1.7% and 0.7% to the pulsed fraction of sinusoidal and X-ray pulse shapes in the range $111 \text{ s} < P < 143 \text{ s}$. This null result was interpreted as due to smearing and suppression effects due to the large dimension of the $H\alpha$ emitting region, $r_{H\alpha} \sim 6 \times 10^{13}$ cm, as calculated by Davidsen et al. (1977). The escape time for $H\alpha$ photons with an optical depth $\tau_{H\alpha} \sim 10^2$ from a cloud of that size would be $(r_{H\alpha}/c)\tau_{H\alpha} \sim 2 \times 10^5$ sec.

Motivated by the discovery of flickering with time scales of \sim minutes (Braga et al. 1993), and night-to-night variations on the mean R magnitude of up to 0.5 mag, we are conducting a concentrated observational effort trying to answer fundamental questions about this system: what is its orbital period? is this a wind-fed or accretion-disk-fed pulsar? What is the origin of the photometric variability in long and short time scales?

2. Observations and Data Reduction

The data discussed in this paper were obtained with the 1.6-m and 0.6-m telescopes of Laboratório Nacional de Astrofísica, in Brazil. The CCD photometer we have built consists of a Wright Instr. thermoelectrically-cooled camera with a EEV CCD-02-06 back-illuminated chip operated in the frame-transfer mode (385×289 pixels in the image section). The timing for the instrument is provided by a Datum Inc. BC627AT Global Position System (GPS) receiver and timing board installed in the same IBM-PC clone used to read the CCD camera. Integration times down to 1 second are possible, especially with 2×2 on-chip binning.

The plate scale produced by the various combinations of telescopes, focal reducers and binning factors is always $\lesssim 1''.2/\text{pixel}$. The field around V2116 Oph is relatively uncrowded, permitting safe aperture photometry to monitor its brightness relative to several comparison stars.

The reduction of the data is presently done

off-line using a set of IRAF³ scripts written by one of us (FJ). The reduction of a few thousand images, including the standard preparation procedures (bias, dark and flat-field) can be done in the day following the observations.

The data summarized in Table 1 resulted from 20,465 images in the field of V2116 Oph. The CuSO₄ filter used is a 4mm-thickness liquid solution similar to what we have used for many years in the *U* passband of our *UBVRI* photometer (Jablonski et al. 1994). This non-standard passband maximizes photon count without sacrificing too much the capability of doing differential photometry. Column 3 of Table 1 shows the integration time Δt , and column 4 shows the total duration of each run. On 1996 April 26 for instance, the data set consists of 3300 sequential images of 5 s integration time each.

Each night, a few images in the *R* filter were obtained to provide a long-term light curve of the system. Since we have determined photoelectrically the magnitude of star #9 in the chart of Doxsey et al. (1977) ($V = 13.39 \pm 0.04$, $V - R = +0.77 \pm 0.02$, $R - I = 0.79 \pm 0.01$) even nights of poorer photometric quality provide good magnitude measurements for V2116 Oph. This is the same comparison star used in the H α photometry of Greenhill et al. (1995). Column 5 of Table 1 lists the mean *R* magnitude of V2116 Oph in each observational run.

3. Analysis

Figure 1 shows the light curve of V2116 Oph obtained with the CuSO₄ filter on 1996 April 26, where the optical pulsations with 124 s were first detected (Jablonski et al. 1996). The comparison stars observed simultaneously (two of them are shown in this figure) provide a very good estimate of the noise in the variable star's light

curve.

Figure 2 shows the power spectrum of the light curve in Figure 1. The dotted line marks the expected level of noise estimated from the light curves of six comparison stars measured simultaneously. The isolated feature close to 0.008 Hz has peak power ~ 200 times the power in the local continuum. A discrete periodogram with increased frequency resolution gives a better estimate of the period of that feature: 124.17 ± 0.04 s. There are two interesting additional pieces of information in Figure 2: the inclination of the power spectrum at low frequencies, $\alpha = 2.01 \pm 0.05$ in $\text{Power} \propto f^{-\alpha}$, and the period where this component intercepts the noise level, $P_0 = 57 \pm 2$ s. The flickering behavior of V2116 Oph is very similar to that shown by cataclysmic variables (Bruch 1992). An estimate of the amount of flickering in the light curves is given in the last column of Table 1. It measures the excess power above the photon noise level, integrated in the frequency range 0.001 – 0.005 Hz. We follow van der Klis (1989) and express this quantity in terms of percentage r.m.s. variation in the light curve.

The detection of stable optical pulsations with period close to what is expected from the X-rays history of GX 1+4 prompted us to observe the system as often as possible. Table 1 shows a summary of all subsequent observations. In the case of a detection, the barycentric period and the semi-amplitude of the pulsed signal are shown in columns 6 and 7. In Figure 3 we plot the periods listed in Table 1 together with the results from the continuous monitoring by BATSE. The very good quality of the X-rays daily period determinations results from the large modulation fraction and from the use of five-day segments in the analysis (Chakrabarty et al. 1997).

4. Discussion

We can summarize the results of this paper as follows:

We have detected optical pulsations in V2116

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Oph with periods very close to the expected from the X-rays history of GX 1+4 (Chakrabarty et al. 1997). This adds a third object to the small group of accreting pulsars that are LMXB and present optical pulsations. The other cases are HZ Her \equiv Her-X1 (Davidsen et al. 1972; Middleditch & Nelson 1976) and KZ TrA \equiv 4U1626-67 (Ilovaisky, Motch & Chevalier 1978; Middleditch et al. 1981).

We interpret the presence of flickering in the light curves as evidence of an accretion disk in the system. The power spectrum shown in Figure 2 indicates that the variations due to flickering appear on time scales as short as 57 s before they get immersed on the flat noise component due to photon statistics. If we associate the shortest time scale for flickering in our data, namely 57 s, with the radius of a Keplerian orbit in the accretion disk, we obtain a dimension $r \sim 2.5 \times 10^9$ cm, for a $1.4M_\odot$ neutron star. In other words, if we associate r with an upper limit on the magnetospheric radius r_M (Frank, King & Raine 1992), then the fastness parameter ω_s in the theory of Ghosh & Lamb (1979a,b) would be ≈ 0.5 . This is consistent with $\omega_s < 1$ needed for steady accretion. The standard theory (Frank et al. 1992) also gives an estimate of the surface magnetic field of the neutron star, $B_0 \approx 10^{14}$ G, assuming a typical luminosity of 10^{37} erg s $^{-1}$. This is consistent with a previous estimate by White (1988).

The absence of flickering when the system is faint (the total r.m.s. variation above photon noise in the light curve of June 19 is $\lesssim 1\%$) indicates that the accretion may stop episodically. This is consistent with the observed low states in X-rays (Chakrabarty & Prince 1996) contemporaneous with very low levels of H α emission (Sood et al. 1996). If Roche lobe overflow is the preferred accretion mode in GX1+4, we are forced to conclude that the M companion does not fill its lobe all the time. This is expected if the M-giant presents large-scale mass motions in its outer layers, like red irregular and semi-

regular variables usually do (Querci 1986). Besides providing episodes of low accretion, semi-regular variations in the accretion flux could also be a good explanation for the so called “300 days” cycle in the torque history of the neutron star (Cutler, Dennis & Dolan 1986; Chakrabarty et al. 1997).

The origin of the optical pulsed emission cannot be determined from the data discussed in this paper, but taking what happens in HZ Her and KZ TrA as a paradigm, it could be a combination of reprocessing of X-rays in the accretion disk, in the atmosphere of late-type star, and in the stream between the latter and the disk (Middleditch & Nelson 1976; Middleditch et al. 1981). From the observed colors of the DC and pulsed light on 1996 May 27, we estimate the absolute magnitude of the pulsed component to be $M_V \sim -1.5$ for a distance of ~ 10 kpc and $E(B - V)$ in the range $1.8 - 2.0$ (Jablonski & Pereira 1997). If the pulsed light follows a black-body spectral distribution with temperature $T_{BB} = 10^5$ K, the size of the emitting region would be $\sim 1.1R_\odot$. For lower temperatures, 2×10^4 K and 1×10^4 K, we obtain dimensions of $3.2R_\odot$ and $7.0R_\odot$, respectively. The correspondent areas are not prohibitive either as fractions of the surface area of the companion star or as fractions of an accretion disk area. The accretion stream is ruled out as a likely sole source of the pulsations because its projected area is too small. If the pulsations show a dependence with orbital phase, like in HZ Her and KZ TrA, the long term monitoring of the optical pulsations may be useful to answer a long-lasting (and very basic) question about this system: what is the orbital period of GX 1+4 ? So far, we only know that in order to fill the corresponding Roche lobe, a M4-6 III star with 80-100 R_\odot would need $P_{\text{orb}} \gtrsim 100$ days in a binary with mass ratio $q \sim 1$.

The BATSE measurements (Chakrabarty et al. 1997) show that it is very difficult to measure the orbital period of the system from the Doppler effect on the X-ray pulses alone, by the follow-

ing reasons: the orbital period is long, probably $\gtrsim 100$ d, the orbital inclination may be low (though this is less certain), and it is very difficult to separate the effects of the spin-down (and its fluctuations) from the Doppler effect itself on a long-period orbit. Our best determination of pulse period, namely 124.17 ± 0.04 s, on April 26, is significantly different from the BATSE measurement, 123.9453 ± 0.0014 s, based on a linear interpolation between the daily values of Chakrabarty et al. (1997). If caused by Doppler effect, the implied difference in velocity between the X-ray and optical emitting regions would be $\sim 540(\sin)^{-1}i$ km/s, too high for a binary with the characteristics discussed earlier.

By analogy with HZ Her and KZ TrA we expect to see sidebands of P_{opt} or P_X according to $P_{\text{opt}}^{-1} = P_X^{-1} - P_{\text{orb}}^{-1}$. If we try to explain the observed difference between P_{opt} and P_X in terms of sidebands, then the derived P_{orb} is too small, ~ 0.8 days, again inconsistent with our previous knowledge about this system. A good observational coverage will settle this point, in particular if we are able to track the *phase* of the pulsations from simultaneous measurements in the optical and X-ray bands.

The relatively long period and large amplitude of the optical pulsations in V2116 Oph open interesting perspectives for future work. Likely projects include the detailed history of the pulsations on a night-to-night basis and its correlation with the X-ray timings, a spectrophotometric study of the optical and NIR spectrum of the pulsations and the correlation of the visibility of the pulsations with orbital phase.

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REFERENCES

- Braga, J., Jablonski, F., D'Amico, F., Elizalde, F., & Steiner, J. 1993, *Rev. Mex. Astr. Astrof.*, 26, 113
- Bruch, A. 1992, *A&A*, 266, 237
- Chakrabarty, D. & Prince, T. 1996, *IAU Circ.* No. 6478
- Chakrabarty, D., Bildsten, L., Grunsfeld, J. M., Koh, D. T., Nelson, R. W., Prince, T. A., Vaughan, B. A., Finger, M. H., & Wilson, R. B. 1997, *ApJ*, submitted
- Cieslinski, D., Elizalde, F., & Steiner, J. E. 1994, *A&AS*, 106, 243
- Cutler, E. P., Dennis, B. R., & Dolan, J. F. 1986, *ApJ*, 300, 551
- Davidson, A., Henry, J. P., Middleditch, J., & Smith, H. E. 1972, *ApJ*, 177, L97
- Davidson, A., Malina, R., & Bowyer, S. 1977, *ApJ*, 211, 866
- Doxsey, R.E., Apparao, K.M.V., Bradt, H.V., Dower, R.G., & Jernigan, J.G. 1977, *Nature*, 270, 586
- Frank, J., King, A., Raine, D. 1992, *Accretion Power in Astrophysics*, 2nd ed., (Cambridge: Cambridge Univ. Press)
- Ghosh, P. & Lamb, F. K. 1979a, *ApJ*, 232, 259
- Ghosh, P. & Lamb, F. K. 1979b, *ApJ*, 234, 296
- Glass, I.S., & Feast, M. W. 1973, *Nature Phys. Sci.*, 245, 39
- Greenhill, J.G., Watson, R.D., Tobin, W., Pritchard, J.D., & Clark, M. 1995, *MNRAS*, 274, L61
- Ilovaisky, S. A., Motch, C., & Chevalier, C. 1978, *A&A*, 70, L19
- Jablonski, F., Baptista, R., Barroso Jr., J., Gneiding, C. D., Rodrigues, F., & Campos, R. P. 1994, *PASP*, 106, 1172
- Jablonski, F., Pereira, M. G., Braga, J., & Gneiding, C. D. 1996, *IAUC Circ.* No. 6489
- Jablonski, F., & Pereira, M. G. 1997, in preparation
- Querci, F. R. 1986, in *The M-type Stars*, ed. S. Jordan & R. Thomas, (NASA SP-492)(Washington: U.S. Government Printing Office), 1
- Krzeminski, W. & Priedhorski, W.C. 1978, *PASP*, 106, 566
- Laurent, P., Salotti, L., Paul, J., Lebrun, F., Denis, M., Barret, D., Jourdain, E., Roques, J. P., Churazov, E., Gilfanov, M., Sunyaev, R., Diachkov, A., Khavenson, N., Novikov, B., Chulkov, I., & Kuznetsov, A. 1993, *A&A*, 278, 444
- Makishima, K., Ohashi, T., Sakao, T., Dotani, T., Inoue, H., Koyama, K., Makino, F., Mitsuda, K., Nagase, F., Thomas, H. D., Turner, M. J. L., Kii, T., & Tawara, Y. 1988, *Nature*, 333, 746
- Manchanda, R.K., James, S.D., Lawson, W.A., Sood, R.K., Grey, D.J., & Sharma, D.P. 1995, *A&A*, 293, L29
- McClintock, J. E., Leventhal, M. 1989, *ApJ*, 346, 143
- Middleditch, J., & Nelson, J. E. 1976, *ApJ*, 208, 567
- Middleditch, J., Mason, K. O., Nelson, J. E., & White, N. E. 1981, *ApJ*, 244, 1001
- Mony, B., Kendziorra, E., Maisack, M., Stauber, R., Englhauser, J., Döbereiner, S., Pietsch, W., Reppin, C., Trümper, J., Churazov, E. M., Gilfanov, M. R., & Sunyaev, R. 1991, *A&A*, 247, 405
- Nagase, F. 1989, *PASJ*, 41, 1
- Predehl, P., Friedrich, S. & Staubert, R. 1995, *A&A*, 294, L33
- Rao, A. R., Paul, B., Chitnis, V. R., Agrawal, P. C., and Manchanda, R. K. 1994, *A&A*, 289, L43
- Sood, R., James, S., Lawson, W., Manchanda, R., and Heisler, C. 1996, *IAU Circ.* No. 6496

- Shahbaz, T., Smale, A. P., Naylor, T., Charles, P. A., van Paradijs, J., Hassal, B. J. M., & Callanan, P. 1996, MNRAS, 282, 1437
- Staubert, R., Maisack, M., Kendziorra, E., Draxler, T., Finger, M. H., Fishman, G. J., Strickman, M. S., & Starr, C. H. 1995, Adv. Space Res. 15, (5)119
- van der Klis, M. 1989, in Timing Neutron Stars, ed. H. Ogelman & E. P. J. van den Heuvel (NATO ASI Ser. C, 262)(Dordrecht: Kluwer), 203
- White, N. E. 1988, Nature, 333, 708

Fig. 1.— Differential photometry CCD light curve of V2116 Oph on 1996 April 26, with 5 s time resolution. The differential light curves of two nearby stars are shown for comparison. The brightest star is object # 10 in the chart of Doxsey et. al (1977). The inset shows a section where individual pulses can be seen. The arrows pointing to subsequent maxima were produced by constant-period (124.17 s) prediction. The small bar in the upper right corner of the inset shows the estimated level of noise in that section of the light curve.

Fig. 2.— The power spectrum of the light curve in Figure 1. The horizontal dashed line shows the estimated level of noise derived from the light curves of six comparison stars measured simultaneously. The inset shows the light curve folded on the 124.17 s period. The phase interval is repeated twice for better visualization and the vertical scale is relative amplitude.

Fig. 3.— The period of the optical pulsations listed in Table 1 (filled circles) together with the BATSE daily measurements (crosses; Chakrabarty et al. 1997).

TABLE 1
FAST PHOTOMETRY OF V2116 OPH

Date (1996)	Filter	Δt (s)	Duration (hrs)	R (mag)	Barycentric period (s)	Semi-amplitude (%)	Flickering ^f (%)
Apr 26 ^a	CuSO ₄	5	4.6	15.48	124.17±0.04	1.3±0.1	2.3
May 21 ^b	CuSO ₄	15	4.2	15.26	124.1±0.3	0.6±0.3	2.5
May 25 ^c	CuSO ₄	20	0.4	15.29	124.6±1.6	1.8±0.5	0.7
May 26 ^c	CuSO ₄	10	0.9	15.29	124.2±0.9	1.2±0.4	1.9
May 27 ^c	CuSO ₄	20	0.9	15.28	124.0±0.3	4.3±0.5	1.7
May 27 ^c	R	20	0.8	15.28	124.1±0.4	2.6±0.4	2.0
May 27 ^{ad}	Clear	15 ^e	0.7	15.28	124.5±0.5	2.5±0.4	1.4
May 27 ^{ad}	U	15 ^e	0.7	15.28	...	<12	8.6
May 27 ^{ad}	B	15 ^e	0.7	15.28	...	<4.4	4.8
May 27 ^{ad}	V	15 ^e	0.7	15.28	124.1±1.0	5.3±1.6	4.6
May 27 ^{ad}	R	15 ^e	0.7	15.28	124.6±0.6	3.3±0.6	1.7
May 27 ^{ad}	I	15 ^e	0.7	15.28	124.1±0.6	2.2±0.4	1.3
May 28 ^c	CuSO ₄	20	1.5	15.37	123.9±0.5	1.7±0.6	2.5
May 28 ^c	R	20	1.7	15.37	124.3±0.5	0.6±0.2	1.1
Jun 19 ^a	Clear	5	7.0	17.72	...	<0.05	0.1
Jun 20 ^a	Clear	5	6.6	17.68	...	<0.07	0.2
Jul 13 ^b	R	25	3.7	17.01	124.1±0.2	0.9±0.3	1.2
Aug 04 ^b	R	20	3.0	15.67	124.2±0.3	0.4±0.2	0.5
Aug 05 ^b	R	20	4.4	15.45	124.0±0.4	0.2±0.2	1.3
Aug 06 ^b	CuSO ₄	20	3.3	15.28	124.7±0.3	0.4±0.1	0.6
Aug 07 ^b	R	20	1.7	15.29	...	<0.1	0.5
Aug 18 ^b	Clear	10	1.4	15.99	...	<0.15	0.2
Aug 19 ^b	R	20	3.0	16.29	...	<0.33	0.5
Aug 20 ^b	R	25	4.2	16.09	...	<0.17	0.3
Aug 22 ^b	R	25	5.7	16.94	...	<0.16	0.9

^a1.6-m telescope

^b0.6-m Zeiss telescope

^c0.6-m Boller & Chivens telescope

^dFOTRAP photometer

^eTime resolution instead of integration time

^fIntegrated in the range 0.001 – 0.005 Hz





